A model-based evaluation of Marine Protected Areas: the example of eastern Baltic cod (*Gadus morhua callarias* L.)

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The eastern Baltic cod stock collapsed as a consequence of climate-driven adverse hydrographic conditions and overfishing and has remained at historically low levels. Spatio-temporal fishing closures [Marine Protected Areas (MPAs)] have been implemented since 1995, to protect and restore the spawning stock. However, no signs of recovery have been observed yet, either suggesting that MPAs are an inappropriate management measure or pointing towards suboptimal closure design. We used the spatially explicit fishery simulation model ISIS-Fish to evaluate proposed and implemented fishery closures, combining an age-structured population module with a multifleet exploitation module and a management module in a single model environment. The model is parameterized based on (i) the large amount of biological knowledge available for cod and (ii) an analysis of existing spatially disaggregated fishery data. As the population dynamics of eastern Baltic cod depend strongly on the climate-driven hydrographic regime, we considered two production regimes of the stock. MPAs were only effective for stock recovery when they reduced overall fishing effort. The performance of MPAs needs to be evaluated relative to environmental regimes, especially for stocks facing strong environmental variability.

Keywords: Baltic cod, fishery management, Marine Protected Areas, model, stock recovery.

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Introduction

Implementing Ecosystem-Based Fisheries Management (EBFM) means the use of closed areas as a management tool to protect at least parts of the marine ecosystem from the adverse effects of fishing (Agardy, 1994). Beyond the preservation of biodiversity in permanently closed areas, it is often expected that closed areas will also provide direct benefits to adjacent fisheries (Halpern and Warner, 2003; Murawski *et al.*, 2005). Yet, these benefits must be proven. Furthermore, because fisheries depend on the productivity of the ecosystem, and fisheries affect the supporting ecosystem of the target species, the design of fishery management measures should take account of environmental variations (e.g. Hutchings and Myers, 1994). However, most fishery models have a limited spatial description and ignore the effects of environmental conditions on the productivity of fish stocks.

Adoption of the EBFM approach fostered the development of comprehensive models that account for trophic interactions (e.g. Walters *et al.*, 1999; Watson *et al.*, 2000; Pinnegar *et al.*, 2005). However, the spatially explicit description of interactions between resources and fishing activities, including management options, has received less attention (Pelletier and Mahévas, 2005). One reason is that most fisheries are complex systems not only by virtue of the diversity of the exploited resources (multispecies) but also owing to multiple fishing activities (multifleet), which hampered the development of models able to handle this complexity while not oversimplifying the system. Additional complexity arises because EBFM not only considers a range of closure designs but also a number of other management tools that needs to be considered in simulation models. Recently, the generic and spatially explicit fishery simulation model ISIS-Fish (Mahévas and Pelletier, 2004; Pelletier and Mahévas, 2005) was applied to a number of case studies in the Northeast Atlantic and Mediterranean (see Drouineau *et al.*, 2006; Pelletier *et al.*, 2007). We used this model to evaluate the effects of spatio-temporal closures implemented in the central Baltic Sea to support recovery of the eastern Baltic cod stock.

Eastern Baltic cod (*Gadus morhua callarius*) has been depleted for several years. The spawning stock declined from an extremely high level during the early 1980s (~665 000 t in 1982) to a historical low of ∼66 000 t in 2005, as a result of recruitment failure and high fishing intensity, with no sign of recovery (ICES, 2007). In the second half of the 1990s, decreased predation pressure by the cod stock, combined with high reproductive success and relatively low fishing mortalities, resulted in a drastically enlarged sprat (*Sprattus sprattus*) stock (Köster *et al.*, 2003). This switch in dominance was facilitated by the fact that cod recruitment is highly dependent on environmental conditions, which mainly affect the egg and larva stages. Egg survival is determined by oxygen conditions and clupeid predation pressure in the reproduction layers (Köster *et al.*, 2005), whereas larval survival is limited by the availability of suitable prey, and successful settlement in suitable nursery areas is determined by larval transport (Hinrichsen *et al.*, 2009).

Until 2005, exploitation of Baltic fish stocks was managed by the International Baltic Sea Fisheries Commission (IBSFC), mainly through TACs. However, landings frequently exceeded the agreed TACs. Moreover, from 1982 to 1988, the IBSFC was not able to establish a TAC, resulting in an unregulated fishery (Radtke, 2003) over a period of frequent recruitment failure (Köster *et al.*, 2005). In view of the rapid decline of the cod stock during the 1980s, the IBSFC introduced new regulatory measures, such as fishing closures, mesh size regulations, and minimum landing sizes (Radtke, 2003). Two types of fishing closure were enforced to preserve the stock. In 1995, a summer ban of 4.5 months on fisheries targeting cod was implemented. Its duration was subsequently modified with a minimum duration of 2 months in 2007. Second, a specific spawning closure of all fisheries was put in place in a relatively small area east of the island of Bornholm, with size varying over years. It was complemented in 2005 with two closed areas in the Gdańsk Deep (GD) and Gotland Basin (GB) spawning grounds.

Here, we evaluate the performance of past, present, and proposed closures aimed at helping the stock to recover. As the population dynamics of eastern Baltic cod are strongly dependent on the prevailing climate-driven hydrographic regime, we consider alternative production regimes of the stock. These scenarios are based on long-term observations of utilization of spawning areas, recruitment, growth, maturation, survival, and migration patterns. Hydrodynamic drift model results were used to determine suitable nursery grounds (Hinrichsen *et al.*, 2009).

Material and methods

Model description

ISIS-Fish (Mahévas and Pelletier, 2004; Pelletier and Mahévas, 2005) is a model of fishery dynamics based on three submodels: a population model, an exploitation model, and a management model. Each submodel is spatially explicit and operates on a monthly time-step. The model domain, i.e. the fishery region, for eastern Baltic cod is defined by the main distribution area of the stock, ranging from 54° to 59°N and from 14° to 24°E (Figure 1; Bagge *et al.*, 1994). The fishery region is overlaid with a regular grid of spatial resolution 0.25° latitude and 0.5° longitude, corresponding to one-quarter of an ICES statistical rectangle. The spatial resolution of the grid was chosen to match the dynamics of the processes to be described and the precision of the information available for parameterizing the model. Within the fishery region, zones were defined independently for each population area (spawning grounds, nursery areas, and feeding grounds), each fishing activity, and each management measure. Seasons (i.e. sets of successive months) were also defined for each population group (age classes), each fishing activity, and each management measure. Within each zone and season, fishing effort and population abundance were assumed to be homogeneously distributed. Seasonal migrations between population zones are considered, and zone-specific catchability depends on seasons. The exploitation model calculates the standardized effort per fishing activity affecting the population in each zone and month. In ISIS-Fish, fishing units are not individually identified but grouped into fleets described by métiers and strategies. A métier is characterized by a combination of gear, target species, zone, and season. Fishing effort is standardized between gears, and a selectivity model is defined for each combination of gear and species, with a parameter that can possibly be modified through management measures, e.g. mesh size. Vessels that practise a similar sequence of métiers during the year constitute a fishing strategy characterized by a seasonal allocation of fishing effort between métiers. The management model describes the management scenario considered, its impact on the fishing activity, in particular attributable to fishers' response to management. At each time-step, the model calculates changes in the distribution of fishing effort among métiers of a strategy and generates the corresponding catch and abundance estimates for each zone. Further details and the equations are given in Pelletier and Mahévas (2005).

Population model

Zones

Eastern Baltic cod traditionally utilize three well-separated spawning grounds in the Bornholm Basin (BB), GD, and GB. Spawning grounds were delineated from the long-term average distribution pattern of the youngest egg stage (Bagge *et al.*, 1994; Hinrichsen *et al.*, 2007) and were defined as zones in the model (Figure 1a).

Two scenarios were considered in the model, corresponding to distinct climate and hence stock productivity regimes. The first is a "good" environmental scenario, where hydrographic conditions (i.e. inflow of oxygen-rich waters) favour cod reproduction, and all three spawning grounds produce viable offspring (Figure 1a). The second is a "bad" environmental scenario, where hydrographic conditions are adverse for cod reproduction and recruitment. In this case, the easternmost spawning ground, i.e. GB, is not utilized owing to oxygen depletion in the spawning layers (MacKenzie *et al.*, 2000). Feeding areas were assigned to each of the three spawning grounds and defined as slope regions of the deep spawning basins (Figure 1b). Nursery areas were defined based on long-term simulations (1974–2003), with a hydrodynamic model developed by Lehmann (1995). Virtual cod larvae were used as Lagrangian drifters to simulate potential settlement areas (Hinrichsen *et al.*, 2009). In the population model, for each spawning ground, corresponding nursery areas were defined as model cells, where the average settling probability of juveniles from the spawning ground was >10% (Figure 1c).

Migrations

Migration from feeding areas to spawning grounds is age-specific and lasts from February until May (Tomkiewicz and Köster, 1999). After spawning, all age groups gradually migrate, from July to September, to the feeding areas that are closest to their spawning grounds. We assumed no differences between age groups in the timing of the migration from the spawning areas to feeding areas (Tomkiewicz and Köster, 1999). Immature age-2 recruits

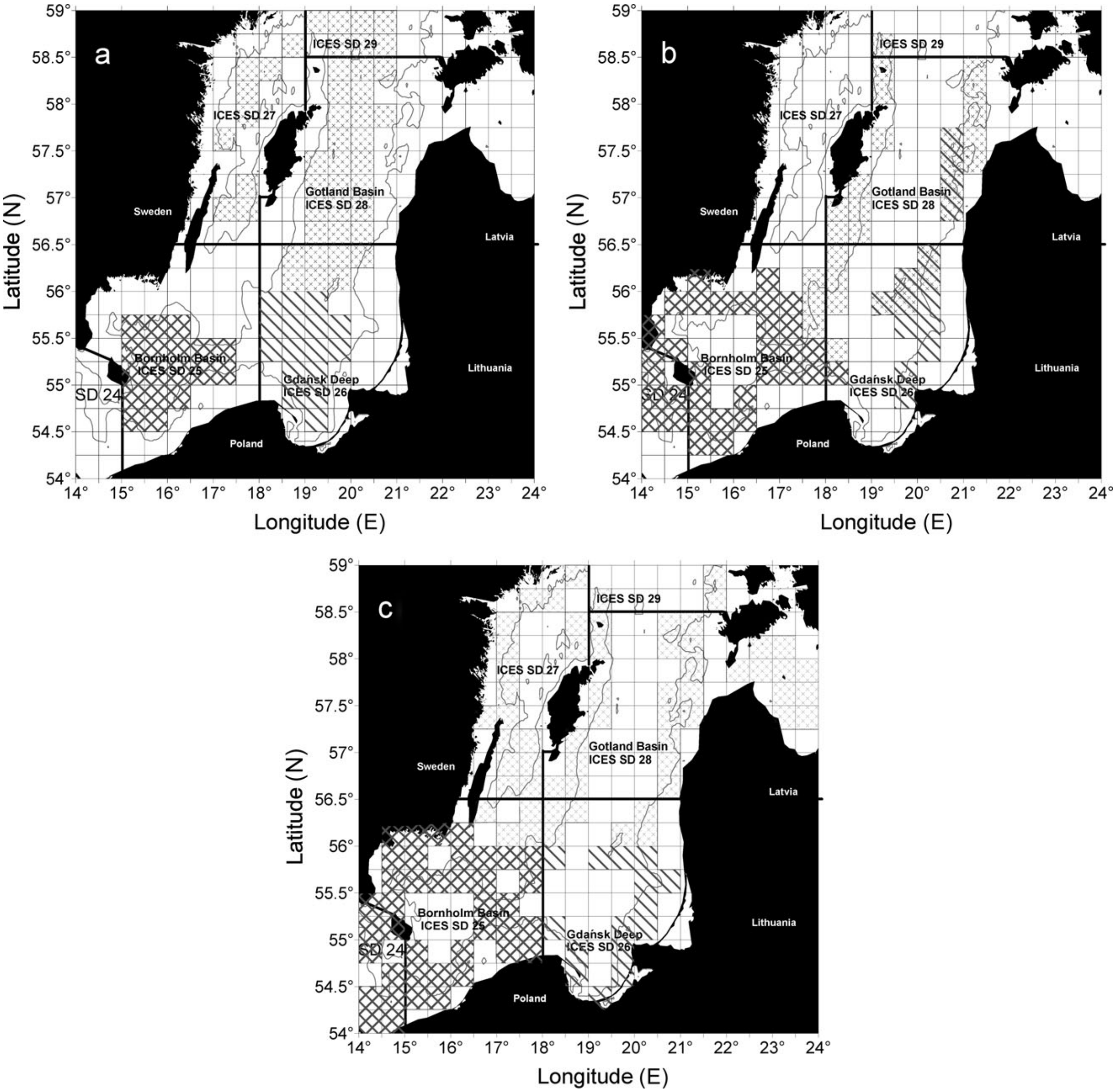

Figure 1. Population zones considered in the ISIS-Fish model: (a) spawning areas, (b) nursery areas, and (c) feeding areas. Population zones corresponding to the GB stock component are indicated by an x pattern. A diagonal crossed-line pattern was assigned to zones of the BB stock component, and diagonal-line patterns to the GD stock component.

were assumed to migrate from their nurseries to the nearest feeding area in one movement in September. A conceptual model of the eastern Baltic cod life cycle is provided in Figure 2.

In the good scenario, migrations happen only within a region (GB, GD, and BB; see Figure 1), i.e. between corresponding nursery, feeding, and spawning areas. In the bad scenario, the GB spawning ground is not utilized but may produce recruits as a result of easterly larval drift from the GD and BB spawning areas. As no detailed information on migration of these recruits is available, we assumed immature age-2 recruits from the GB nursery area to migrate first to their corresponding GB feeding ground. Upon maturation, they were evenly distributed between the BB and GD spawning grounds. The spawning migration of the adult stock and mature age-2 recruits from the BB and GD feeding grounds was parameterized based on observed and scenario-specific distribution patterns from the ICES Baltic International Trawl Survey database. Two-thirds of these fish distribute to the BB spawning ground and one-third to the GD spawning ground.

Population parameters

The cod population was structured into seven classes from age 2 to 8. All fish older than 8 years were accumulated in the last class, and von Bertalanffy growth curves were defined for each environmental scenario based on observed length converted weight-at-age data. Similarly, the mean weight-at-age for each environmental

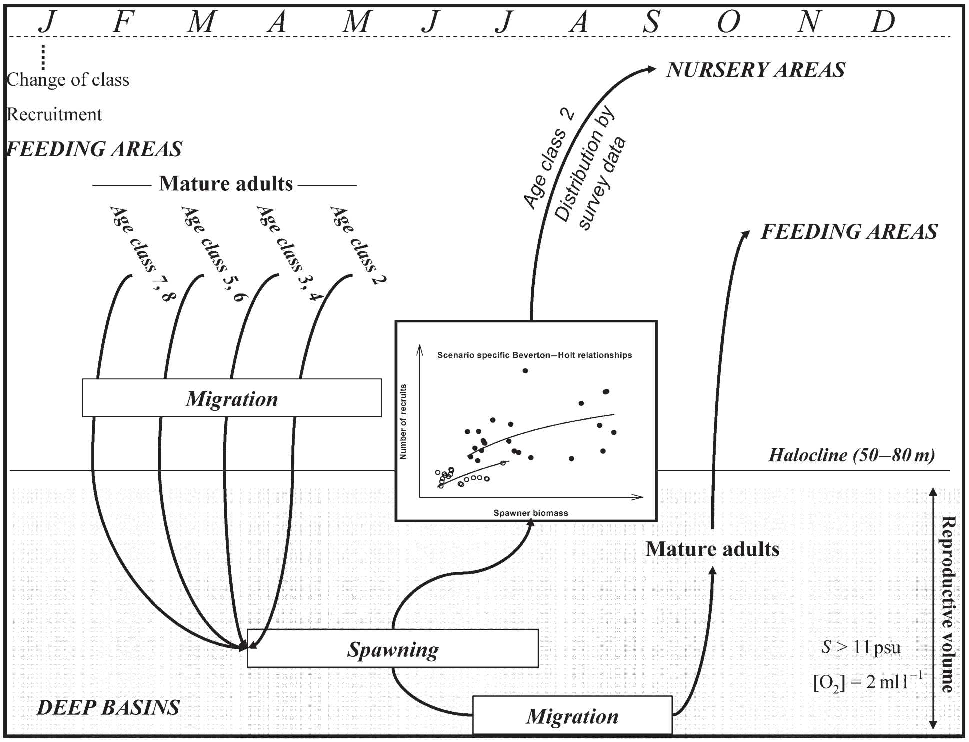

Figure 2. Conceptual diagram of the population model for eastern Baltic cod including migrations. The horizontal plane visualizes the seasonal development (month initials given in the top line). The vertical plane displays the depth gradient from cod spawning in the deep Baltic basins to feeding and recruiting at the shallow basin slopes and coastal regions.

scenario was obtained by fitting exponential weight-at-age curves. Natural mortality was assumed to be 0.2 for all age classes. Spawning–stock biomass (SSB) was calculated from stock numbers and scenario- and area-specific observed maturity ogives. Total SSB was summed over all population areas and fed into a common but scenario-specific Beverton–Holt stock–recruit relationship. The resulting total abundance of immature age-2 recruits was redistributed between the three nursery areas using observed and scenario-specific distribution patterns from the ICES Baltic International Trawl Survey database. Detailed information on population parameters and related references are given in Table 1.

Exploitation model

On average, 83% of cod catches are taken by Poland, Sweden, Denmark, Germany, and Latvia, with ICES Subdivisions (SDs) 25 and 26 being the most intensively fished areas in the central Baltic Sea. The main fisheries for cod in the eastern Baltic use demersal trawls, pelagic trawls, and gillnets, representing more than 99% of the total catch (ICES, 2007).

The exploitation model was parameterized from logbook data from the five countries. Data include catch and effort (in days at sea) for 1995–2005. Fishing by other countries in the central Baltic Sea amounts to 13% of the total fishing effort and was accounted for by increasing the effort proportionally among fleets represented in the model.

Data were available per month, ICES statistical rectangle, vessel size group, gear type, and country. Three vessel size groups were considered: <12, 12–24, and >24 m. An average trip duration was assigned to each of these groups, and three main gears were considered, namely trawls, gillnets, and "other gears", the last mainly consisting of longlines. Selectivity curves for the main gears (trawls and gillnets) were taken from R. Nielsen (pers. comm.; Table 2). For other gears, an average selectivity curve was computed from the previous two gears, because no specific data on selectivity were available. The standardization factor of a gear F_{std} quantifies the ratio in the overall catch between each gear and a reference gear (i.e. the difference in efficiency between gears). Standardization factors were estimated for each gear by fitting a generalized linear model (GLM) to logbook catch per unit effort (cpue) data. The model is loglinear with the factors gear, month, and zone, including an interaction between month and zone. For a given gear, the standardization factor F_{std} was estimated as the back-transformed gear effect of the model. It was equal to 1.71 for trawls and to 1.16 for other gears using gillnets as reference gear.

As the only target species in the model was cod, métiers were defined based on fishing zones, gears used, and fishing seasons for that species. In all, 23 métiers and 19 corresponding fishing zones were identified (see Appendix). A fishing zone was defined as a group of contiguous statistical rectangles making up at least ~80% of the fishing effort of that métier.

For a single target species in the model, the target factor F_{target} depicts differences in fishing efficiency between métiers, including fishers' *savoir-faire*. F_{target} was calculated by fitting a GLM to logbook cpue, while taking into account the standardization factor F_{std} calculated earlier. The model is a loglinear model of cpue/F_{std}, with the factors vessel size group, month, and zone. F_{target} was estimated as the back-transformed vessel size group effect of the model. Using small vessels as the reference vessel

Table 1. Estimated population parameters used in the ISIS-Fish model.

Parameters	Values	Source
General parameters		
Number of age groups	7	ICES (2007)
Growth	von Bertalanffy:	ICES (2007)
	"good environment"	
	$K = 0.064$, Linf = 187.55 cm, and T0 = −1.086	
	"bad environment"	
	$K = 0.101$, Linf = 145.154 cm, and T0 = −0.727	
Stock–recruit relationship	Beverton–Holt:	ICES (2007)
	"good environment"	
	Recr A2 = (2.35 × SSB)/(1 + 0.000006 × SSB)	
	"bad environment"	
	Recr A2 = (1.15 × SSB)/(1 + 0.000005 × SSB)	
Age-specific parameters		
Natural mortality	0.2 for all age groups and scenarios	ICES (2007)
Weight-at-age	"good environment"	ICES (2007)
	weight = −1.3070993 + exp(0.204730 × age)	
	"bad environment"	
	weight = −1.3094575 + exp(0.2206051 × age)	
Maturity	curve: $y = a/[1 + (x/x_0)^b]$	Tomkiewicz *et al.* (1997) and ICES (2007)
	"good environment"	
	$a = 0.9943$; $x = -5.066$; $x_0 = 3.111$	
	"bad environment"	
	$a = 1.0083$; $x = -4.781$; $x_0 = 3.00151$	

Table 2. Selectivity curve parameters for each gear.

Gear	S1	S2
Gillnets	37.99	0.92
Trawls	14.87	0.34
Other gears	26.43	0.63

S1 and S2 correspond to the equation $s(x) = 1/[1 + \exp(S1 - S2 \times x)]$, where x is the fish length in centimetres.

size group, F_{target} was equal to 1.44 for medium vessels and 1.72 for large vessels. Finally, strategies were defined from the monthly allocation of effort (logbook data) between the different métiers practised by a set of vessels (small, medium, and large).

Catchability in ISIS-Fish is defined as the probability that a fish present in a specific zone during a season is caught by a standardized effort unit from a non-selective vessel (Pelletier and Mahévas, 2005). Catchability coefficients were fitted by calibrating the model against total quarterly catches over an arbitrarily chosen period of 2 years (2002/2003; Figure 3). Calibration was based on the simplex method (Walters *et al.*, 1991). As cod form dense pre-spawning and spawning aggregations, relatively larger catchability coefficients were assigned to months corresponding to the presence of spawners on the spawning grounds. For simplicity, age effects were ignored, and only two catchability coefficients were estimated for spawning and non-spawning fish (respectively, 8.04×10^{-6} and 1.17×10^{-5}).

Management model

Management options considered in the model included the exclusion of fishing effort at different temporal and spatial scales. When a métier was partly affected by a closure, its fishing effort was assumed to redistribute among the cells of its fishing area located outside of the closure. When the entire fishing area of a métier fell into the closed area, the effort of that métier was set to zero.

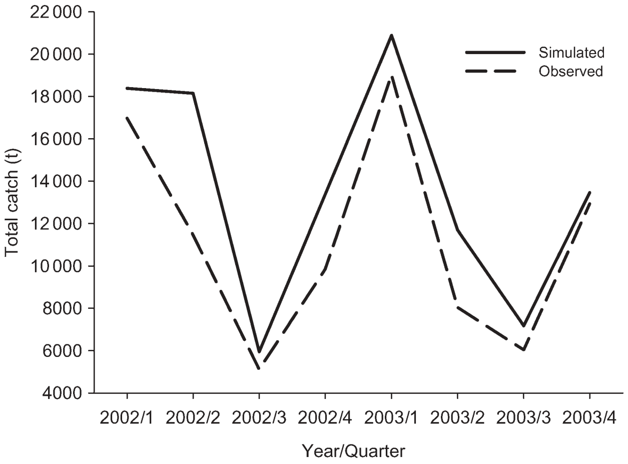

Figure 3. Calibrated quarterly effort pattern applied in the model (solid line). The calibration is based on observed quarterly cod catches (dashed line) for 2002/2003, using the simplex method to minimize the differences between simulated and observed catches and estimate catchability coefficients.

Four scenarios were simulated over the 20-year period, each under conditions favourable and unfavourable to cod reproduction (Table 3). The first set of simulations considered no closures,

Table 3. Simulated scenarios and corresponding figures, closure design, season, and years of implementation (reference is given where applicable).

Scenario	Simulation period	Simulated management measures	Reference
Baseline scenario	2006–2025	No closures	–
1995 scenario	1995–2019	Summer ban from 15th April to 31st August for targeted cod fishing in ICES SD 25–32	IBSFC (1994); reviewed in ICES (1999)
		Spawning closure for all fishing activities in a small area in the BB from 15th May to 31st August	
2007 scenario	2006–2025	Spawning closures in the BB, GD, and southern GB from 15th June to 30th September; passive large meshed gears allowed	COM (2006) 485 final
		Summer ban from 15th June to 14 September for targeted cod fishing in ICES SD 25–27	
		10% reduction of days at sea compared with 2006 fishing days	
Large spawning closure scenario	2006–2025	Large, year-around spawning closure in the BB and GD/southern GB	–

using initial stock sizes for 2005, i.e. the most recent year where an area-disaggregated multispecies stock assessment (MSVPA) was available, providing the required area-specific initial stock sizes for the model (ICES, 2005). However, because ICES (2007) estimated the reported landings to be on average 40% lower than the true landings during most recent years and ∼10% of the total catch being discarded, simulations were run with and without correction for misreporting and discarding. To avoid using two different model calibrations, the correction was done by proportionally increasing the effort levels of all fleets until the landings increased by 50%. In the following, the scenarios without closures but corrected for misreporting and discarding will be referred to as “baseline scenarios”.

Then, the effects of a single, small spawning closure in the BB combined with a closed season were simulated, based on the IBSFC management plan for 1995 (Table 3; Figure 4a and d). For this scenario (denoted here as “1995 scenario”), initial stock sizes from area-disaggregated MSVPA for 1994 were used (ICES, 2005). The third set of simulations comprised three small spawning closures plus a closed season, based on the management plan proposed by the EU Commission for 2007, where the 10% reduction in days at sea included in the management plan was accounted for by extending the closed season (Table 3; Figure 4b and d). Finally, two large, year-round spawning ground closures in the BB and GD were considered (Table 3; Figure 4c). For the last two scenarios (denoted here as “2007 scenario” and “large spawning closure scenario”), the most recent area-specific MSVPA estimates for 2005 were used as initial stock sizes for the simulations (ICES, 2005).

Results

The baseline scenario did not consider closed areas or seasons, but was used to demonstrate the effect of misreporting and discarding on the dynamics of SSB and yield (Figure 5a and b). Note that we have chosen to display the annual average SSB rather than SSB at the start of the year, because SSB on 1 January is strongly influenced by the strength of the recruiting year classes, whereas the annual average SSB already accounts for exploitation of the youngest recruited year class. The effect of misreporting and discarding was most dramatic under adverse environmental conditions, because the annual average SSB continued to decline to levels below 50 000 t (Figure 5a). Even if reported catches were the true catches, the stock would recover only slowly to an SSB of ∼140 000 t after 20 years of simulation, which is still below the present biomass limit reference point of 160 000 t. For both scenarios, the total annual yield remained relatively stable at low level, but an increasing trend was observed in the simulation with the uncorrected landings, with yield reaching a maximum of ∼45 000 t after 20 years, which corresponded to the trend in SSB (Figure 5a).

Under favourable environmental conditions, the stock recovered irrespective of the correction for discard and misreporting (Figure 5b). Recovery appeared to be slower with the correction. The final SSB was about half of the size compared with the results obtained without correction. Therefore, yield increased more slowly in the simulation with the correction. However, for both scenarios, the total annual yield after 20 years reached the same plateau, indicating a maximum catching capacity of ∼110 000 t under the current parameterization of the model.

In a second step, we evaluated the 1995 closure scenario using 1994 area-disaggregated MSVPA stock numbers as initial stock

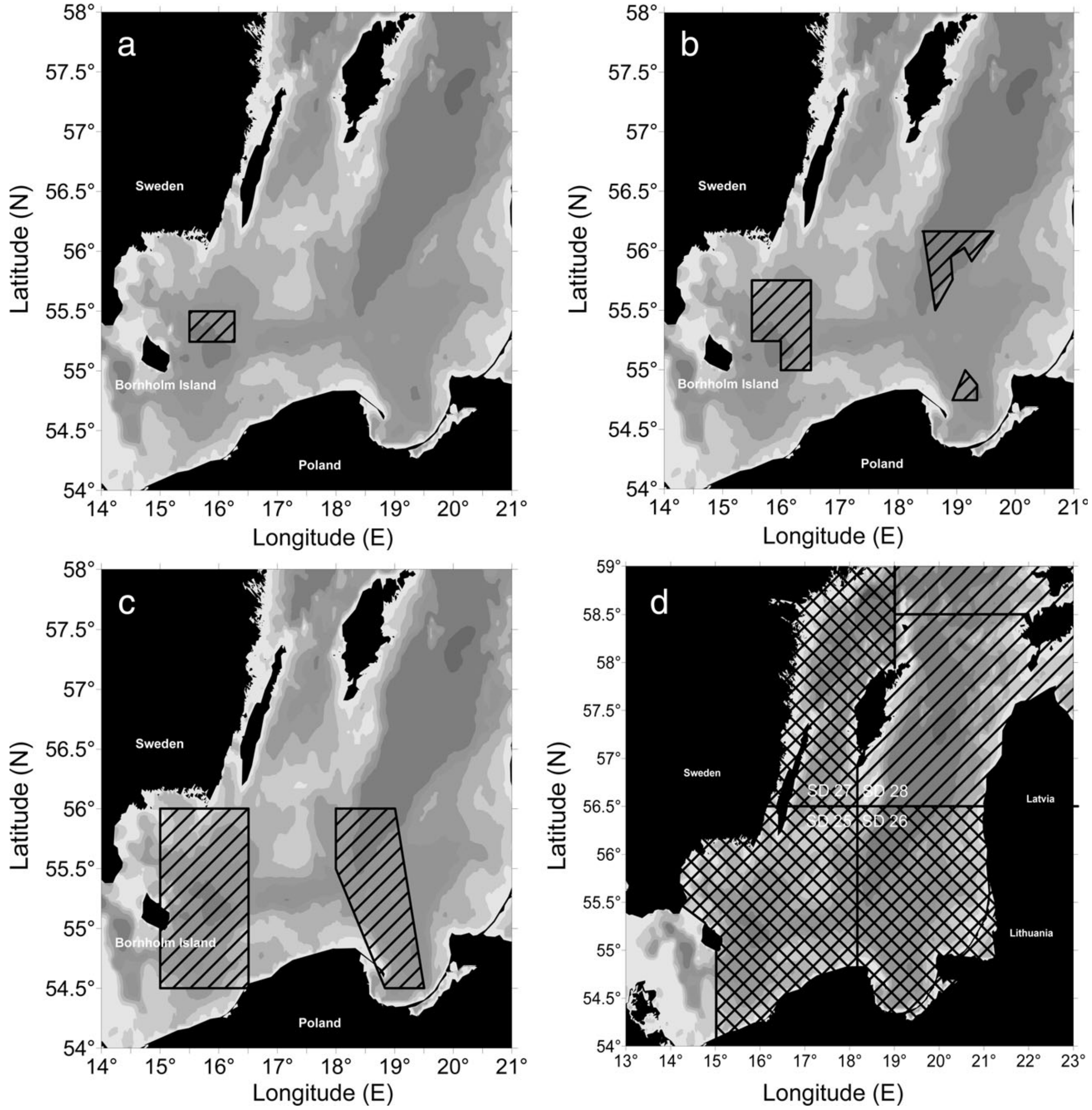

Figure 4. Spawning closures aimed at restoring eastern Baltic cod: (a) implemented from 1995 to 2003, and used in the "1995 scenario"; (b) implemented since 2004, and used in the "2007 scenario"; (c) suggested by the EU Commission for 2006, and used in the "large spawning closure scenario"; (d) depicts the areas of the model domain affected by the summer bans of the targeted cod fishery for the "1995 scenario" (entire central Baltic Sea) and the "2007 scenario" (ICES SDs 25–27).

sizes (Figure 6). Under adverse environmental conditions, SSB remained relatively stable below $B_{\lim}$ at ~115 000 t, however, with a slightly decreasing trend leading to a final total SSB of 112 000 t after 20 years. After an initial drop, yield stabilized after 4 years at ca. 50 000 t. Under favourable environmental conditions, SSB steadily increased over the simulation period and exceeded 400 000 t after 20 years. Following SSB increase, yield increased to ca. 110 000 t after 20 years.

Lastly, we simulated the 2007 and the large spawning closure scenarios (Table 3). These can be compared with the baseline scenario because the simulation periods were the same. Under favourable environmental conditions, both SSB and catch increased substantially with the 2007 scenario (Figure 7a), whereas the consequences of the large spawning closures were similar to the baseline scenario, i.e. the latter closure scenario was ineffective in terms of both SSB and yield under favourable environmental conditions (Figure 7b). This may be explained by the fact that most métiers were able to displace their effort beyond the closure boundaries and maintain similar catch levels. However, during the first 10 simulation years of the large spawning closure scenario, SSB was constantly a few tonnes below the baseline scenario, which can be interpreted as an effect of effort

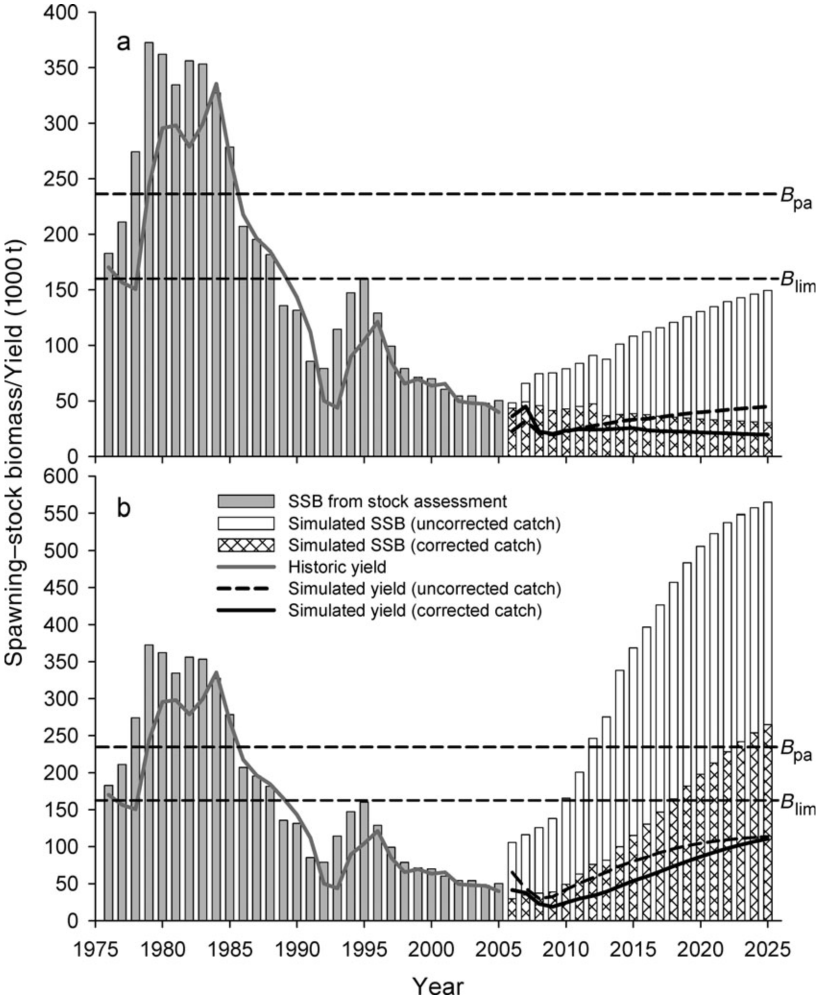

Figure 5. Trajectories of annual average SSB (bars) and total annual yield (lines) without fishing closures implemented. Results are shown for (a) adverse and (b) favourable environmental conditions. In each case, results are displayed with and without correction of reported catches for misreporting and discarding; 1976–2005 annual average SSB and total annual yield as estimated from an area-disaggregated multispecies VPA by quarter are also shown. The corresponding limit (B_{lim}) and precautionary (B_{pa}) reference points are displayed as horizontal lines (ICES, 2007).

displacement into regions of higher catchability compared with the traditional fishing grounds. For adverse environmental conditions, SSB under the large spawning closure scenario remained relatively stable at very low levels, with the final SSB after 20 years of simulation being 20 000 t higher than under the baseline scenario and still much lower than B_{lim} (Figure 7b). Similar to SSB, yield stayed stable and reached a total of 27 000 t at the end of the simulation period, which was only slightly higher than the baseline scenario. With respect to the 2007 scenario, SSB doubled over the simulation from 50 000 t to slightly more than 100 000 t (Figure 7a). Contrary to SSB, the increase in yield from ca. 30 000 t to 40 000 t was less pronounced.

It is difficult to compare the 1995 scenario directly with the other two closure scenarios, because they do not start from the same years or initial stock sizes. Initial stock sizes were much lower for the 2007 scenario and large spawning closure scenario (SSB 50 000 t) than for the 1995 scenario (SSB 147 000 t). At the end of their respective simulation periods, however, the SSB levels reached in the 2007 and 1995 scenarios were similar, respectively, above 400 000 t (favourable conditions) and ca. 110 000 t (unfavourable conditions; Figures 6 and 7a). This seems to indicate a stabilization of the dynamics of the population, which can be expected given the assumption of a Beverton–Holt stock–recruit function. Therefore, catch levelled off between 123 000 t (1995 scenario) and 113 000 t (2007 scenario) under favourable environmental conditions, which is only a minor deviation from the baseline scenario (110 000 t), indicating that the population was fully exploited.

None of the scenarios investigated allowed the stock to recover even to B_{lim} level under unfavourable conditions. In contrast, under favourable conditions, B_{pa} was reached after 9 years with the 1995 scenario, after 13 years under the 2007 scenario, and after 18 years under large spawning closures (Figures 6 and 7a and b). Note that this last result was also obtained in the baseline scenario without closures (Figure 5b).

To disentangle the effects of small and large spawning closures as well as closed seasons, an additional simulation was conducted with only the three small spawning closures of the 2007 scenario being implemented, i.e. leaving aside the closed season of that scenario. In this exercise, we only considered adverse environmental conditions, because favourable environmental conditions led to stock recovery irrespective of closed areas or seasons. The

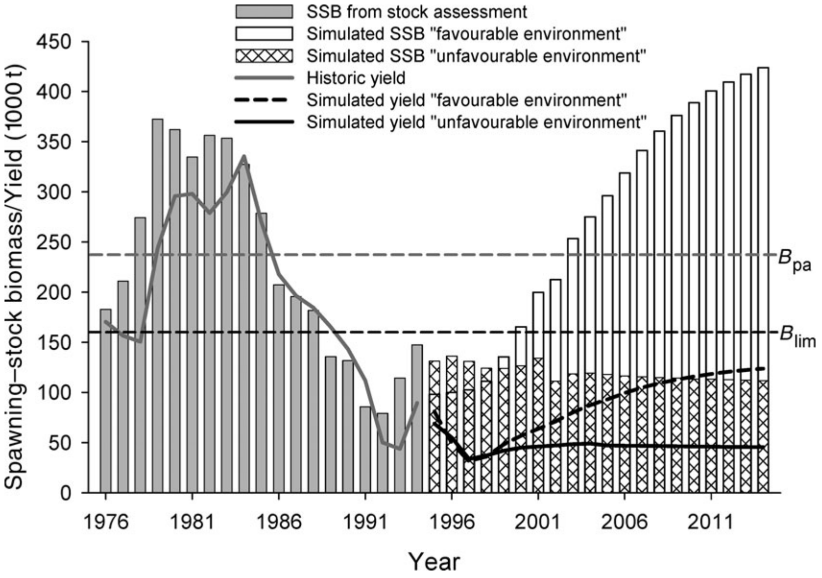

Figure 6. Trajectories of annual average SSB (bars) and total annual yield (lines). Simulations were run based on corrected catches, but considering the closures of the "1995 scenario". Scenarios were simulated for adverse and favourable environmental conditions; 1976–1994 annual average SSB and total annual yield as estimated from an area-disaggregated MSVPA by quarter are also shown. The corresponding limit (B_{lim}) and precautionary (B_{pa}) reference points are displayed as horizontal lines (ICES, 2007).

SSB trajectory over the 20-year simulation period revealed no effect of the small spawning closures, because the results were similar to those of the baseline scenario (Figure 8). In contrast, the large spawning closure scenario differed moderately from the baseline SSB stabilizing the stock. A positive SSB development could be observed when the full 2007 scenario, including the seasonal closure, was implemented (Figure 8).

Discussion

The primary management measures for demersal stocks in the Baltic Sea are TACs. These are accompanied by an extensive array of technical measures, including seasonal closures, closed areas, additional restrictions of days at sea to be allocated individually by the Member States, minimum landing sizes, and regulations concerning codend mesh configuration (ICES, 2007). Consequently, a detailed evaluation of the separate effects of each of the management measures on the stock and fishery was hardly possible. Unlike Drouineau *et al.* (2006), who applied ISIS-Fish to the hake and *Nephrops* fishery in the Bay of Biscay, we did not attempt to disentangle the effects of several measures jointly implemented, but chose rather to evaluate specific closure scenarios either already implemented or proposed.

The ISIS-Fish model of the Baltic cod fishery is the first application of the model to a fish population with a comprehensive amount of biological and ecological knowledge. Based on the available biological time-series data and output from a coupled biophysical model for eastern Baltic cod (Hinrichsen *et al.*, 2009), we were able to construct and parameterize the population model for two contrasting environmental regimes, which allowed us to study the effects of different management options under varying environmental forcing conditions.

In contrast to short-term stock predictions, medium-term stock projections as conducted in the present study depend heavily on the recruitment model (Gislason, 1993). Most of the processes determining year-class strength, as well as growth, maturation, and survival during the adult life, are reasonably well understood for eastern Baltic cod. A main driver of recruitment variability is the thickness and oxygen content of the reproductive volume for cod eggs affecting egg survival (Nissling *et al.*, 1994; MacKenzie *et al.*, 2000; Köster *et al.*, 2003, 2005). These two variables are affected by the frequency and intensity of inflow events of oxygen-rich water masses from the western Baltic and North Sea, which in turn are determined by regional atmospheric forcing and long-term climate fluctuations (Matthäus and Franck, 1992; Mohrholz *et al.*, 2006). It is mainly the limited, long-term predictability of the regional climate and related changes in the hydrographic conditions that impair realistic recruitment predictions, and thus projections, of future population development of Baltic cod. Consequently, we considered Beverton–Holt recruitment models, fitted to periods characterized by distinct environmental regimes, to account for differences in stock productivity during favourable and adverse environmental conditions. Similar to recruitment, environment-dependent growth, maturation, spawning, and migration functions were also parameterized, based on the available datasets (STORE, 2002; ICES, 2005, 2007) and implemented in the population model. As we explored two extreme environmental regimes between which most conditions will range, it can be expected that our two scenarios would also represent the upper and lower extremes of population development. The difference in population sizes may thus serve as a valid indicator of model sensitivity to these biological hypotheses.

These differences in population size and yield between the two environmental scenarios were by far larger than the effects of the discard and misreporting correction, as well as the influence of the applied management scenario. A similarly strong environmental signal on population abundance and yield was revealed in earlier studies (ICES, 2005; Röckmann *et al.*, 2007). However, these studies considered scenarios of fixed fishing mortalities at limited spatial resolution (i.e. ICES SDs) and were not depicting fleets.

An important error source related to the exploitation model is the high rate of misreporting in the Baltic cod fishery. Whereas discards are regularly sampled with a good coverage, misreporting

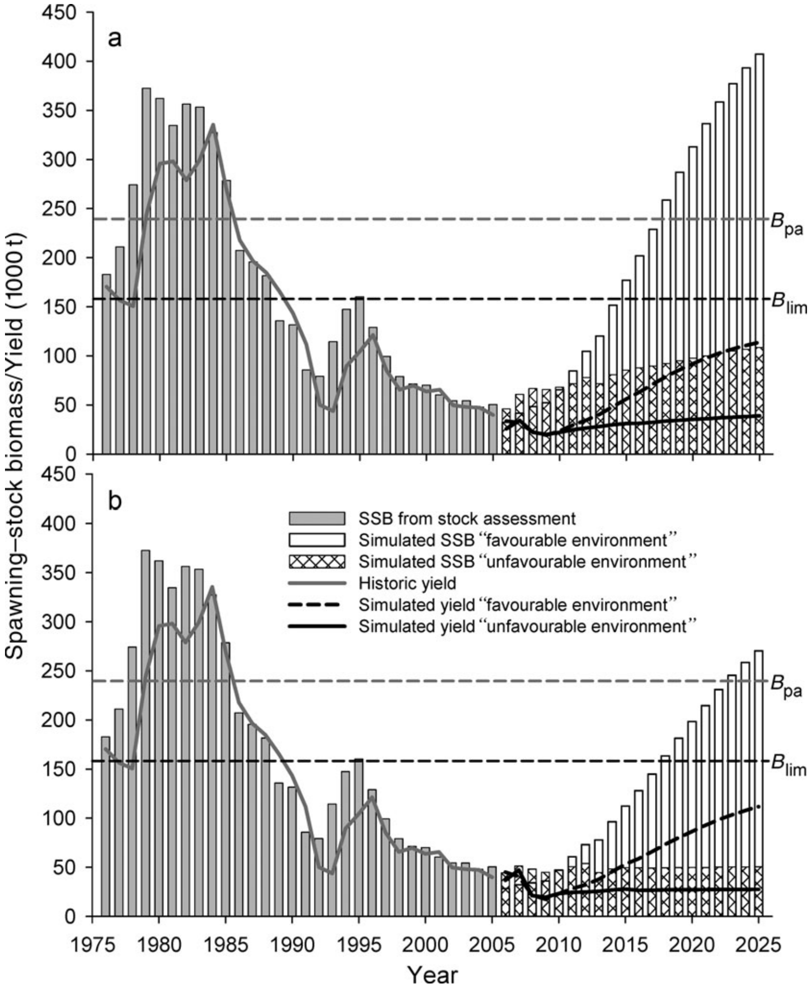

Figure 7. Trajectories of annual average SSB (bars) and total annual yield (lines). Simulations were run based on corrected catches, but considering the closures of (a) the "2007 scenario", and (b) the "large spawning closure scenario". In each case, scenarios were simulated for adverse and favourable environmental conditions; 1976–2005 annual average SSB and total annual yield as estimated from an area-disaggregated MSVPA by quarter are also shown. The corresponding limit (B_{lim}) and precautionary (B_{pa}) reference points are displayed as horizontal lines (ICES, 2007).

leads to substantial uncertainty in total landing estimates (ICES, 2007). In recent years, ICES has attempted to correct for such misreporting by applying raising factors to national catches, based on the information available on misreporting for each national fleet. However, this information is highly uncertain and incomplete by nature, with no information available for some nations where, nonetheless, misreporting is suspected to occur. Although catches used in the present study were corrected for misreporting, using information provided by ICES, they can at best be considered to be approximate minimum values (ICES, 2007). As a result, our simulations may provide an overly optimistic picture, but because the correction for misreporting and discarding was done by increasing the effort equally throughout all métiers, model runs with and without correction provide an indication of the model's sensitivity to variations in overall exploitation levels.

Under favourable environmental conditions, a simulation without closures revealed a stock recovery to levels around B_{pa} after 18 years, even when the effort was increased to account for illegal landings and discarding. This indicates that the current total effort would be sustainable in the long run under such conditions. However, unfavourable conditions are known to occur frequently, and future climate change is not expected to improve environmental conditions for cod reproduction in the Baltic Sea. Westerly airflows have intensified, especially during winter, contributing to higher winter temperatures, greater precipitation, and reduced inflow activity (BACC, 2008). Studies of past and recent ecosystem changes have demonstrated the sensitivity of the Baltic Sea ecosystem to changing temperatures. Several effects could be related to temperature changes, in particular, to changes in species composition. For instance, higher temperatures during the 1990s were associated with a shift in dominance within the open-sea copepod community from *Pseudocalanus acuspes* to *Acartia* spp. (Möllmann and Köster, 1999). Survival of Baltic cod larvae is strongly dependent on the occurrence of *P. acuspes* in their prey field (Hinrichsen *et al.*, 2002). These trends are expected to continue in future according to regional climate change scenarios (BACC, 2008). Therefore, sustained periods of favourable environmental conditions for cod reproduction, as considered in some of the simulations, are unlikely in future.

On the contrary, under unfavourable environmental conditions, none of the proposed or implemented closure scenarios were able to recover the stock even to B_{lim}. Such a scenario of

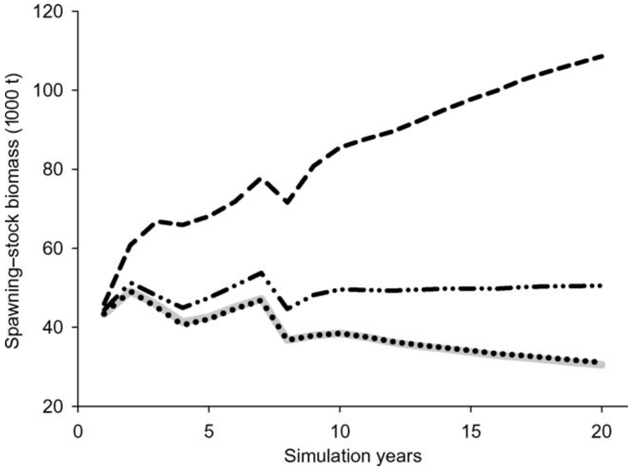

Figure 8. Comparison of the consequences of different closures on SSB development over 20-year simulation periods: no closures (grey line), three spawning closures of the "2007 scenario" (black dotted line), "large spawning closure scenario" (black dash-and-dot line), and the full "2007 scenario" including three small spawning closures plus a seasonal closure (black dashed line). Simulations were run based on corrected catches and adverse environmental conditions.

consistently low recruitment might be overly pessimistic, because even during long stagnation periods, infrequent inflows were observed (Mohrholz *et al.*, 2006). These events would improve the strength of single or several year classes and consequently the resilience of the stock against heavy exploitation.

As both population and exploitation models are subject to some uncertainty as described above, the interpretation of SSB and yield should be cautious. Still, a relative comparison of different closure regimes under otherwise constant conditions provides valuable insight into the performance of closures such as those tested here. For example, our results demonstrated that closed seasons of the entire fishing area had a much greater impact on recovery rates, final stock sizes, and yield compared with regionally restricted spawning area closures. This observation is in contrast to Halliday (1988), who could not demonstrate positive effects when analysing seasonal closures on Georges Bank to preserve haddock. Even the large spawning closure scenario, affecting about one-fifth of the entire fishing area year-round, performed remarkably worse than the tested seasonal closures. Although this scenario effectively removed all effort from dense prespawning and spawning concentrations, the capacity of the cod fleets was obviously high enough to compensate the closure effect to a large degree by reallocating the effort into open areas and maintaining high catch levels. In addition, effort may be reallocated into potentially sensitive nursery areas with additional negative population effects not accounted for in our model (Hinrichsen *et al.*, 2009).

Another possible reason for the limited impact of spawning closures might lie in the effort reallocation rule implemented in our model. We assume that effort is eliminated from the fishery only if a métier falls completely into a closure, i.e. assuming that these métiers would leave the area and search for other distant fishing options, whereas the effort of partially affected métiers is reallocated. As the spatially restricted spawning closures in the Baltic Sea affected most métiers only partly, the largest portion of the effort is reallocated into open cells of the métiers along the boundaries of the closures, as also documented by Murawski *et al.* (2005) for Georges Bank, whereas the large-scale seasonal closures effectively reduced the overall fishing pressure also from potentially sensitive nursery areas (Hinrichsen *et al.*, 2009). However, the positive effects of large spawning closures may prove greater than shown here, because economic constraints, such as increasing travel time and fuel costs imposed on fleets in relation to the closure, were not accounted for in the present model. Moreover, large, year-round closures may also have positive effects on stock structure that are beneficial to adjacent fisheries (Roberts *et al.*, 2001), but are not accounted for in our model, e.g. an increase in the number of large, fecund fish.

Despite the strong and obvious influence of environmental conditions, we conclude that, conditioned on model assumptions for effort reallocation, the reduction of effort, and thus fishing mortality as imposed by closed seasons, is more efficient at promoting stock recovery than reduction of spawner disturbances through the implementation of spatially restricted spawning closures. As our model fleets are parameterized based on catch data comprehensive for the entire Baltic cod fishery, we are certain that this conclusion will also hold for the existing cod fleets, i.e. catch losses imposed by closed seasons cannot be fully compensated during other times of the year.

An effective, traditional management regime may therefore be a viable alternative to the MPA design currently implemented in the Baltic Sea, which is well in line with other studies on the effects of MPAs on temperate, highly mobile fish species (Hilborn *et al.*, 2004; Kaiser, 2005). We must acknowledge, however, that our present model ignores multispecies interactions, effects of spawning closures on protection of large, fecund females, and possible effort reallocation effects on sensitive nursery areas. Yet, it would be interesting to investigate effort reallocation schemes further, e.g. through the analysis of vessel monitoring systems or fisher interviews, to better parameterize fishers' response to MPA implementation.

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Appendix

Gear used, vessel sizes, fishing zones (with corresponding ICES statistical rectangles), and seasons for each métier considered in the model. Seasons are labelled in months (T, trawl; G, gillnet; O, other gears; vessel sizes 1, <12 m; 2, 12–24 m; 3, >24 m).

Gear and vessel size	Métier	Fishing zone	ICES rectangles (% effort)	Total effort (%)	Season (months)
T-1	Denmark 1.1	Denmark 1	39G5(56.44) 39G4(27.25) 38G5(16.31)	100	J F M A J J A S O N D
T-1	Sweden 1	Sweden1	40G4(33.43) 40G5(60.54)	93.88	J F M A S O N D
T-2	Denmark l.2	Denmark 1	39G5(41.06) 38G5(14.27) 39G4(23.12)	78.49	J F M A M J J A S O N D
T-2	Germany l	Germany 1	38G4(25.81) 39G5(19.13) 38G5(15.46) 40G6(11.79) 37G4(9.56) 39G4(8.01) 39G6(6.79)	96.55	J F M A M J J S O N D
T-2	Poland 1	Poland 1	39G8(16.38) 38G8(15.10) 38G5 (14.48) 39G7(14.01) 38G9(9.24) 37G5(7.18) 38G7(5.52) 39G6(5.08) 38G6(3.98)	90.97	J F M A M S O N D
T-2	Sweden 2	Sweden 2	40G4(28.85) 40G5(20.57) 40G6(15.55) 39G4(15.51)	80.48	J F M A S O N D
T-3	Germany 2	Germany 2	40G6(26.68) 38G5(25.84) 39G5(25.84) 39G6(7.87) 38G4(5.62)	91.45	J F M A M S O N D
T-3	Latvia 1	Latvia 1	41G9(66.13) 42H0(4.44) 42G9(3.68) 41H0(3.6)	77.85	J F M A M S O N D
T-3	Poland 2	Poland 2	39G8(28.9) 39G6(13.04) 39G7(13.04) 40G8(13.01) 38G5(10.42) 38G6(7.48) 39G5(3.33) 38G8(2.62) 38G9(2.3) 39G9(1.98) 40G7(1.64) 37G5(1.04) 38G7(0.56)	99.36	J F M A M S O N D
T-3	Sweden 3	Sweden 3	40G6(33.9) 40G4(18.43) 40G5(14.22) 41G7(8.27) 41G6(5.42) 39G6(4.97)	85.21	J F M A S O N D
G-1	Denmark 1.3	Denmark 1	39G5(43.1) 38G5(28.2) 39G4(19.02)	90.32	J F M A M J J A S O N D
G-1	Poland 3	Poland 3	37G5(36.96) 38G6(20.5) 38G7(11.75) 38G8(6.75) 37G8(6.65) 38G5(5.09) 37G4 (4.23)	91.93	J F M A M J J A S O N D
G-1	Sweden 4	Sweden 4	40G4(31.38) 40G5(14.07) 41G6(8.84) 41G5(8.65) 39G4(7.61) 42G6(6.92) 43G7(4.21) 43G6(3.25) 41G4(2.55) 40G6(2.34) 41G7(2.05) 42G7(l.83)	93.8	J F M A M J J A S O N D
G-2	Poland l.2	Poland l	39G7(23.55) 38G6(16.54) 39G8(13.38) 39G6(11.91) 38G8(8.87) 37G5(7.72) 38G5(6.21) 38G7(6.03) 38G9(O.4)	94.21	J F M A M S O N D
G-2	Sweden 5	Sweden 5	40G5(26.98) 41G6(20.4) 41G7(7.94) 40G4(7.82) 40G6(5.96) 42G7(4.81) 42G6(4.31) 43G7(3.33) 43G6(3.17)	84.72	J F M A M S O N D
G-3	Latvia 2	Latvia 2	41H0(35.4) 40G7(12) 41G9(10.21) 40G6(9.45) 41G7(8.78) 41G8(5.48) 42H0(4.17)	85.49	J F M A M S O N D
G-3	Poland 4	Poland 4	39G7(44.34) 40G7(26.77) 39G8(13.92) 40G8(7.43)	92.46	J F M A M S O N D
O-1	Denmark 2	Denmark 2	39G4(48.53) 38G5(24.27) 38G4(8.04) 39G5(6.96)	87.8	J F M A M S O N D
O-1	Poland 5.l	Poland 5	38G6(30.49) 37G5(27.33) 39G6(10.64) 38G7(9.9) 39G7(9.43) 38G5(7.58) 37G6(2.58)	97.95	J F M A M S O N D
O-1	Sweden 6	Sweden 6	40G4(57.97) 41G5(15.12) 41G4(1l.85) 40G5(9.36)	94.3	J F M A M J J A S O N D
O-2	Poland 5.2	Poland 5	38G6(29.89) 39G7(23.69) 39G6(13.41) 37G5(10.22) 38G7(7.04) 38G5(6.07) 37G6(0.6)	90.92	J F M A M S O N D
O-2	Sweden 7	Sweden 7	40G5(24.53) 40G4(18.5) 40G7(13.92) 39G5(9.77) 39G4(6.86) 41G7(6.02) 41G6(5.2) 38G5(5.2) 40G8(3.19) 41G8(2.7) 39G6(1.87) 40G6(1.25)	93.71	J F M A M J J A S O N D
O-3	Latvia 3	Latvia 3	41H0(79.39) 42H0(8.4)	87.79	S O N D